

MeV Tau Neutrino in Gauge Mediated Supersymmetry Breaking Model

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Abstract

A supersymmetric model which naturally accommodates MeV tau neutrino within the framework of gauge mediated supersymmetry breaking is described. The lepton number violation is originally introduced in the messenger sector of the theory. A large slepton-Higgs mixing mass and a small lepton-higgsino mixing mass are generated at one-loop. Scalar tau neutrino has non-vanishing vacuum expectation value. These results in a non-zero ν_τ mass which is in the range of $(1 - 10)$ MeV.

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I. Introduction

Massive τ -neutrino with mass in the range of $1 - 10$ MeV is an interesting scenario for astrophysics and cosmology [1]. It should have lifetime of $0.1 - 100$ sec [1] or sufficient annihilation rate [2]. As summarized in Ref. [1], it can relax the big-bang nucleosynthesis bound to the baryon density and the number of neutrino species; allow big-bang nucleosynthesis to accommodate a low ($< 20\%$) ${}^4\text{He}$ mass fraction or high ($> 10^{-4}$) deuterium abundance; improve significantly the agreement between the cold dark matter theory of structure formation and observation; and help to explain how type-II supernova explodes.

Due to the useful phenomenological consequence, it is interesting to see if there is a natural way to accommodate the MeV tau neutrino. It can be achieved by introducing right-handed neutrinos into the Standard Model (SM). To make the mass range natural, the Majorana mass scale of the right-handed neutrinos should be properly chosen. And fermion family symmetry may be further introduced to keep the e-neutrino and μ -neutrino being light. This τ -neutrino must decay or annihilate, *e.g.* into light neutrinos and massless boson [3], fast enough to avoid the overclosure of the universe. Nevertheless, the above logic essentially puts the explanation of the neutrino masses into the same category as that of the other fermion masses.

Within supersymmetry, which is the most favorable framework for physics beyond SM, neutrino masses can have several alternative origins. This is simply because that in this case, the lepton number is no longer automatically conserved at tree level. By assuming the conservation of the baryon number only, practically viable models can be constructed without contradiction to the current experiments. They are the so-called R-parity violating models (with baryon number conservation). In such models, the possible new origins of the neutrino masses can be typically classified into following scenarios. First is the non-vanishing sneutrino vacuum expectation values (vevs) [4,

5]. If the sneutrino vevs are non-zero, neutrino in general gains mass due to its tree-level mixing with neutralinos. A neutrino with the heaviness of several MeV can be generated. The second scenario is due to lepton number violating interactions in superpotential. There are two kinds of these interactions that are renormalizable, the bilinear and the trilinear terms. In case the bilinear terms can be rotated away by redefining Higgs superfield [6], the lepton number violation can all be realized in the trilinear terms. These trilinear interactions induce neutrino masses at the loop level [7]. However, the trilinear coupling constants are so constrained by some phenomenological considerations [8] that this mechanism cannot produce τ -neutrino mass larger than 1 MeV within reasonable range of supersymmetric mass scale. The third possibility lies in the soft supersymmetry breaking terms with lepton number violation [9]. The effect of lepton number violation will be mediated to neutrino masses through loops. The simplest case is just to introduce bilinear mass terms which mix the Higgs boson with scalar neutrinos. They induce the mixing between neutrinos and higgsino, which in turn generates neutrino masses by see-saw mechanism. For the soft masses being around weak scale, neutrino mass of several MeV can be generated [6]³. Both the first and the third kinds of origin for MeV neutrino rely on the deeper structure of the theory, namely the supersymmetry breaking mechanism, because they are closely related to the soft breaking sector.

Within the framework of minimal supergravity, Ref. [11] studied the R-parity violation characterized by bilinear terms in the superpotential. They are the most relevant terms to heavy neutrino mass. Generally, they result in the sneutrino vevs which might be around 100 GeV. Such large values, however, do not mean 100 GeV heavy neutrino masses, because there is an almost alignment in the mass matrix [5]. In other words, by a suitable choice of basis, the bilinear terms are rotated away and the corresponding soft terms are almost rotated away. Effectively, there are only small sneutrino vevs in this basis which can give τ -neutrino mass ranging from sub-eV to

³A recent discussion was made in Ref. [10].

MeV.

In this paper, we consider the MeV τ -neutrino as well as the R-parity violation in the framework of gauge mediated supersymmetry breaking (GMSB). We notice that it can be natural that even in the basis where the bilinear terms in superpotential are absent, the theory still allows a relatively large sneutrino vev which is about $1 - 10$ GeV. For such a sneutrino vev, the lepton number breaking must not be spontaneous. Otherwise the corresponding Goldstone boson would result in unacceptable consequences both in astrophysics [12] and in Z decays [13]. Some explicit lepton number violations have to be introduced further, like the soft supersymmetry breaking terms with lepton number violation. This scenario generates MeV neutrino provided that the Zino mass is around $100 - 1000$ GeV. It will be realized in GMSB in next section.

II. The Model

In this section, we construct a simple model which accommodates MeV τ -neutrino within the framework of GMSB. The lepton number violation is introduced originally in the messenger sector of the theory. It then is communicated to the SM sector including the related soft supersymmetry breaking terms. The τ -neutrino mass appears naturally in a way which combines the first and third scenarios described above. The explanation for the soft breaking mass terms with lepton number violation is given.

GMSB theory [14, 15] has drawn a lot of attentions recently. Supersymmetry breaking is communicated from the hidden sector to the observable sector of the theory via gauge interactions. The scale of supersymmetry breaking is comparatively low, so that the flavor changing neutral current processes are sufficiently suppressed. When considering MeV τ -neutrino, we will make use of the observations of Dine and Nelson [15], and Dvali *et al* [16]. They noted that in GMSB the μ problem [17] is rather

severe. Both the μ term which is the mixing mass term of the two Higgs doublets and its corresponding soft breaking B_μ term can be generated at one-loop [16]. Either μ is at the weak scale and B_μ is unnaturally large, or B_μ is at the weak scale and μ is very small. While there are possible solutions of this problem [18], we will not touch this problem in this work. Instead, we apply similar observation to the discussion of another mixing term, that is the one between the lepton and the Higgs doublet.

We extend the model of Dine and Fischler [14] to include the lepton number violation. To keep the other two neutrinos being light, a discrete family symmetry, which is a Z_3 symmetry among the $SU(2)$ doublets of the three generations, is assumed. The gauge group of the model is just $SU(3) \times SU(2) \times U(1)$. The supersymmetric gauge interactions are uniquely determined and can be found in text books. Besides the fields of the particles in the minimum supersymmetric SM, like the left-chiral lepton superfields and their $SU(3) \times SU(2) \times U(1)$ quantum numbers $L_i(1, 2, -1)$ where $i = 1, 2, 3$ for three families, the Higgs superfields $H_u(1, 2, 1)$ and $H_d(1, 2, -1)$, additional set of chiral superfields, which is usually called messenger sector, is introduced:

$$S, S' = (1, 2, -1) , \quad \bar{S}, \bar{S}' = (1, 2, 1) , \quad (1)$$

and

$$T, T' = (3, 1, -2/3) , \quad \bar{T}, \bar{T}' = (\bar{3}, 1, 2/3) . \quad (2)$$

Furthermore, there are three gauge-singlet superfields, X , Y , and V . Y is responsible for supersymmetry breaking, X is related to electro-weak symmetry breaking, and V to lepton number violation.

The superpotential of the model is written as follows,

$$\mathcal{W} = \mathcal{W}_1 + \mathcal{W}_2 , \quad (3)$$

where \mathcal{W}_1 conserves lepton number,

$$\begin{aligned} \mathcal{W}_1 = & m_1(\bar{S}'S + S'\bar{S}) + m_2(\bar{T}'T + T'\bar{T}) + m_3S\bar{S} + m_4T\bar{T} + m_5V^2 \\ & + Y(\lambda_1S\bar{S} + \lambda_2T\bar{T} + \lambda_3V^2 - \mu_1^2) + \lambda_4X(H_uH_d - \mu_2^2) . \end{aligned} \quad (4)$$

In above equation, the Yukawa interactions are omitted which are irrelevant to our discussion. \mathcal{W}_2 violates the lepton number but has Z_3 family symmetry,

$$\mathcal{W}_2 = V(\lambda_5H_uS + \lambda_6\sum_i L_i\bar{S}) . \quad (5)$$

The supersymmetry breaking is communicated to the observable sector by the messengers. The physics related to \mathcal{W}_1 has been discussed thoroughly in Ref. [14]. The only thing different is that we have introduced one more gauge-singlet V . For m_5^2 sufficiently large, V does not develop any vev. The form of the superpotential is not the most general one which follows the symmetry principle. However it is natural in the sense of t'Hooft due to the non-renormalization theorem in supersymmetry. μ_1 is the supersymmetry breaking scale. μ_2 fixes the electroweak scale, namely the vevs of Higgs fields. It therefore contributes to higgsino masses as will be seen explicitly later.

For the superpotential \mathcal{W}_2 , as can be seen, it is the second term of Eq. (5) that violates lepton number. We have freedom to redefine $\frac{1}{\sqrt{3}}\sum_i L_i \equiv L_{\tau'}$ which can be regarded as the weak eigenstate of (ν_τ, τ) superfield, then

$$\mathcal{W}_2 = V(\lambda_5H_uS + \sqrt{3}\lambda_6L_{\tau'}\bar{S}) . \quad (6)$$

It results in effective τ lepton number violating interactions by integrating out the heavy messengers,

$$\mathcal{L}_{\text{eff}}^{\mathcal{L}} = \sqrt{3}\mu_\tau L_{\tau'}H_u|_{\theta\theta} + \sqrt{3}B_{\mu_\tau}A_{\tau'}\phi_u + \text{h.c.} , \quad (7)$$

where $A_{\tau'}$ and ϕ_u denote the scalar fields of the superfields $L_{\tau'}$ and H_u , respectively, and both μ_τ and B_{μ_τ} are generated through one-loop given in Fig. 1,

$$\begin{aligned} \mu_\tau & \simeq \frac{\lambda_5\lambda_6}{16\pi^2} \frac{\mu_1^2}{m_3} , \\ B_{\mu_\tau} & \simeq \frac{\lambda_5\lambda_6}{16\pi^2} \left(\frac{\mu_1^2}{m_3} \right)^2 . \end{aligned} \quad (8)$$

It is easy to see from Eq. (4) that μ_1^2 is the vev of the auxiliary component of Y . From Eq. (8), we have the relation,

$$B_{\mu_\tau} = \mu_\tau \frac{\mu_1^2}{m_3}. \quad (9)$$

μ_1^2 is constrained by the soft masses of the superpartners of the particles in SM. It is natural to take the messenger mass scale 10^3 GeV, and the supersymmetry breaking scale $\mu_1 \sim 10^4$ GeV. In this case, if B_{μ_τ} is chosen to be around electro-weak scale, μ_τ will be very small, which can be achieved by choosing the coupling product $\lambda_5 \lambda_6 \sim 10^{-4}$. Phenomenologically it does not matter to have a small μ_τ . In fact this is what we need as we will see in the following. It should be noted that $L_{\tau'}$ and H_d appear in the superpotential in different ways, so that the term $L_{\tau'} H_u$ cannot be rotated away.

It is necessary to discuss the scalar potential of the theory to see the sneutrino vevs. In this model, besides field Y , the fields that can have non-vanishing vevs are the sneutrinos in the slepton doublets A_i and the neutral components of the Higgs doublets ϕ_u and ϕ_d ,

$$\langle A_i \rangle = \begin{pmatrix} v_i \\ 0 \end{pmatrix}, \quad \langle \phi_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle \phi_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}. \quad (10)$$

Sneutrino vevs are determined by the minimum of the following neutral potential,

$$V_n = V_n^H + 2B_{\mu_\tau} \sum_i v_i v_u + M_A^2 \sum_i v_i^2 + \frac{g_1^2 + g_2^2}{4} \sum_i v_i^2 (v_u^2 + v_d^2), \quad (11)$$

where V_n^H has not been written explicitly which is the Higgs potential irrelevant to sneutrinos. The scalar lepton mass M_A has been calculated in Ref. [14]. Neglecting the Yukawa contribution, $M_A^2 = \frac{3}{8}(\frac{\alpha_2}{4\pi})^2 \Lambda_S^2$ with $\Lambda_S^2 = 8\frac{\lambda_1^2 \mu_1^4}{m_1^2}$. g_1 and g_2 are the $SU(2) \times U(1)$ coupling constants. We expect $v_i \ll v_d$ or v_u so as to keep the lepton universality. Therefore in Eq. (11), all the terms of order v_i^3 and above have been dropped. Straightforward analysis shows that

$$v_1 = v_2 = v_3 = -\frac{B_{\mu_\tau} v_u}{M_A^2 + \frac{1}{2} M_Z^2 \cos 2\beta}, \quad (12)$$

where $\tan \beta = v_u/v_d$. As we have seen that, even after the electro-weak symmetry

breaking, the Z_3 symmetry is still valid. In other words, only τ' -sneutrino has non-vanishing vev,

$$v_{\tau'} = -\frac{\sqrt{3}B_{\mu\tau}v_u}{M_A^2 + \frac{1}{2}M_Z^2 \cos 2\beta}, \quad v_e = v_\mu = 0. \quad (13)$$

Numerically $v_{\tau'}$ can be one order of magnitude lower than v_d , *e.g.* $v_{\tau'} \sim 10$ GeV by taking $M_A \sim 300$ GeV, $B_{\mu\tau} \sim (50 \text{ GeV})^2$. As has been mentioned before, non-vanishing $v_{\tau'}$ implies mixing between τ' -neutrino and neutralinos.

The term $L_{\tau'}H_u$ provides a mixing mass between $(\nu_{\tau'}, \tau')$ and higgsinos. The large $B_{\mu\tau}$ can also cause comparatively large fermion mixing. The $B_{\mu\tau}$ term, which is the mixing mass term between the slepton doublet $A_{\tau'}$ and Higgs doublet ϕ_u , induces a renormalization to the corresponding fermion mixing mass term between $(\nu_{\tau'}, \tau')$ and the higgsino $(\tilde{\phi}_u^+, \tilde{\phi}_u^0)$ which is the superpartner of ϕ_u . At one-loop level, this happens through Zino (for neutral fermion mixing) or Wino (for charged fermion mixing), $A_{\tau'}$ and ϕ_u being the virtual particles with $B_{\mu\tau}$ insertion, as shown in Fig. 2. The loop effect is approximately $\frac{g_2^2}{16\pi^2} \frac{B_{\mu\tau}}{M_{\tilde{Z}}}$. Together with the contribution of μ_τ , the resulting fermion mixing mass $m_{\tau H}$ is

$$m_{\tau H} \simeq \sqrt{3}\mu_\tau + \frac{g_2^2}{16\pi^2} \frac{\sqrt{3}B_{\mu\tau}}{M_{\tilde{Z}}}. \quad (14)$$

Requiring $B_{\mu\tau} \sim (50 \text{ GeV})^2$ implies $\mu_\tau \sim 0.03$ GeV due to Eq. (9). Plus the loop effect, $m_{\tau H} \sim 0.04 - 0.1$ GeV.

Let us now consider the neutral fermion mixing, namely the mixing of ν'_τ and $\tilde{\phi}_u^0$. This will give out the ν_τ mass. For this purpose, the full mass matrix of $\nu_{\tau'}$ and neutralinos should be written down. The Lagrangian for the neutralino masses is given

as

$$-i(\nu_{\tau'} \quad \tilde{\phi}_d^0 \quad \tilde{\phi}_u^0 \quad \tilde{Z} \quad \tilde{X}) \begin{pmatrix} 0 & 0 & m_{\tau H} & av_{\tau'} & 0 \\ 0 & 0 & 0 & av_d & \lambda_4 v_u \\ m_{\tau H} & 0 & 0 & -av_u & \lambda_4 v_d \\ av_{\tau'} & av_d & -av_u & M_{\tilde{Z}} & 0 \\ 0 & \lambda_4 v_u & \lambda_4 v_d & 0 & 0 \end{pmatrix} \begin{pmatrix} \nu_{\tau'} \\ \tilde{\phi}_d^0 \\ \tilde{\phi}_u^0 \\ \tilde{Z} \\ \tilde{X} \end{pmatrix} + \text{h.c.}, \quad (15)$$

where $\tilde{\phi}_d$ and \tilde{X} are the fermion components of H_d and X respectively, $a = (\frac{g_1^2 + g_2^2}{2})^{1/2}$. The determinant of this matrix is approximately $2m_{\tau H}a^2\lambda_4^2v_{\tau'}v_u(v_u^2 + v_d^2)$ by taking $m_{\tau H} \ll av_{\tau'}$. Except for ν_{τ} , the masses of other neutralinos are at the electro-weak scale. Therefore we have

$$m_{\nu_{\tau}} \simeq \frac{m_{\tau H}v_{\tau'}}{M_Z}, \quad (16)$$

which can be naturally within the range $(1 - 10)$ MeV. The eigenstate is

$$\nu_{\tau} = N_{\nu}(\nu_{\tau'} - \frac{v_{\tau'}v_d}{v_d^2 + v_u^2}\tilde{\phi}_d^0 + \frac{v_{\tau'}v_u}{v_d^2 + v_u^2}\tilde{\phi}_u^0), \quad (17)$$

with N_{ν} being the normalization constant. If the induced mass $m_{\tau H}$ were vanishing, it is easy to see that the mass matrix in Eq. (15) would be of rank 4 (instead of 5), despite the sneutrino vev is non-vanishing. The absence of the conventional μ parameter is crucial for the τ -neutrino being very light compared to the weak scale. If a weak scale μ parameter were included, the neutrino mass would be at weak scale or so.

The mixing of the τ' lepton with charginos is not so interesting as that of neutralinos. It just renormalizes slightly the τ lepton and chargino masses. The related mass matrix is

$$(\tau^c \quad \tilde{\phi}_u^+ \quad \tilde{W}^+) \begin{pmatrix} g_Y v_d & -g_Y v_{\tau'} & 0 \\ m_{\tau H} & 0 & g_2 v_u \\ g_2 v_{\tau'} & g_2 v_d & M_{\tilde{W}} \end{pmatrix} \begin{pmatrix} \tau'^- \\ \tilde{\phi}_d^- \\ \tilde{W}^- \end{pmatrix}, \quad (18)$$

where τ^c is the charge conjugate field of the right-handed τ lepton which has a Yukawa coupling g_Y with τ'^- . At this stage, muon and electron are still massless because of

the Z_3 family symmetry. The physical τ lepton state is

$$\tau = N_\tau(\tau' - \frac{v_{\tau'}}{v_d}\tilde{\phi}_d^-) , \quad (19)$$

with N_τ being the normalization constant.

In this kind of supersymmetric model, τ -neutrino only decays via W -boson exchange, $\nu_\tau \rightarrow e^+e^-\nu_e$. The cosmology and astrophysics require a ν_τ lifetime smaller than 100 sec [1]. That means a heavier ν_τ is favored. Taking $m_{\nu_\tau} = 10$ MeV, the lifetime is [19]

$$\begin{aligned} \tau_{\nu_\tau} &\simeq \frac{192\pi^3}{G_F^2 m_{\nu_\tau}^5} \frac{1}{|V_{e\tau}|^2} \\ &\simeq 0.3 \times \frac{1}{|V_{e\tau}|^2} \text{ sec} . \end{aligned} \quad (20)$$

In this case, the $e - \tau$ CKM like mixing is required to be $|V_{e\tau}| \geq 0.05$ ⁴. This needs to be studied after including masses for e , μ and their neutrinos.

Phenomenologically, this model predicts lepton universality violation in the τ lepton decays. It is because ν_τ and τ in Eqs. (17) and (19) do not coincide in form. Compared to the $e - \nu_e$ or $\mu - \nu_\mu$ weak transition, the $\tau - \nu_\tau$ transition amplitude is suppressed by a factor $N_\nu N_\tau(1 + \frac{v_{\tau'}^2}{v_u^2 + v_d^2})$. This factor can be effectively absorbed into the gauge interaction coupling constant g^τ . Therefore it just measures the τ lepton universality violation. With reasonable choice of $\tan\beta$, like $\tan\beta \simeq 2.2$, for $v_{\tau'} \simeq 10$ GeV, the $e - \tau$ universality violation is at 10^{-3} level,

$$g^e : g^\tau = 1 : 0.996 , \quad (21)$$

which is still consistent with experiment [20], but near to the experiment limit.

⁴This requirement is not totally unreasonable. Although the mass hierarchy of neutrinos is huge, that of charged leptons is not. In certain extreme situation, the relation $V_{e\tau} \sim \sqrt{\frac{m_\mu}{m_\tau}} \sim 0.3$ might be hold.

III. Summary and Discussions

In summary, we have described a supersymmetric model which can naturally accommodate MeV tau neutrino within the framework of GMSB. The lepton number violation is introduced in the messenger sector of the theory, which then is communicated into the SM sector at one-loop level. It turns out that a large $B_{\mu\tau}$ term and a small μ_τ term (see Eqs. (7, 8)) are generated. Furthermore, a non-vanishing sneutrino vev (see Eq. (13)) is produced. These results cause, in an interesting manner, a non-zero ν_τ mass which is right in the range of $(1 - 10)$ MeV. Such a mass for tau neutrino and the phenomenological consequence for lepton universality violation can be verified by the experiments in the near future.

We have noted that this kind model is specific as far as the μ -term is concerned. That term is not necessary in the model. The electroweak symmetry is broken due to the introduction of the μ_2 term which can be regarded as an expedient. The explanation of μ_2 , hence the radiative electroweak symmetry breaking, is beyond the scope of this paper. It is reasonable to discuss it when the μ problem in GMSB gets a satisfactory understanding.

This model is of theoretical interest. Firstly, the mechanism of supersymmetry breaking is still an open problem. MeV neutrino in GMSB is worthy to be explored. Secondly, although the MeV neutrino is not intrinsic to the GMSB, the way to achieve it in this paper is very different from that in the supergravity [11]. It allows naturally a rather large sneutrino vev while the bilinear R-parity violation is small. This scenario may have other physical consequences, *e.g.* in the flavor problem [21]. A detailed investigation on them is left for future works.

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FIGURE CAPTIONS

Fig. 1 Superfield diagrams for generating μ_τ (a) and B_{μ_τ} (b). The internal lines with (without) a "×" denote a messenger $\langle VV \rangle$ or $\langle SS \rangle$ ($\langle V^\dagger V \rangle$ or $\langle S^\dagger S \rangle$) propagator. The field Y can also be attached to the V line.

Fig. 2 One-loop diagram for neutral fermion mixing due to the B_{μ_τ} term which is denoted as "×". \tilde{Z} stands for Zino.

Figures

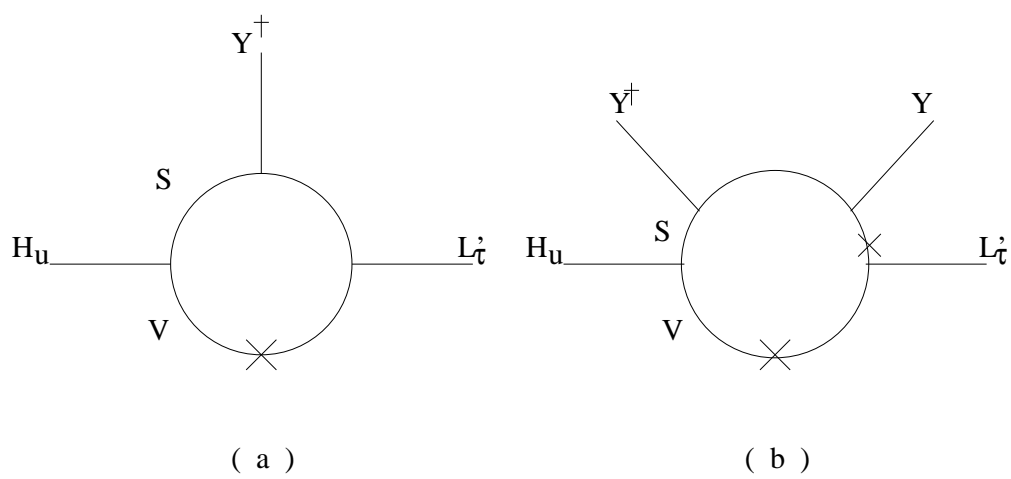


Fig. 1

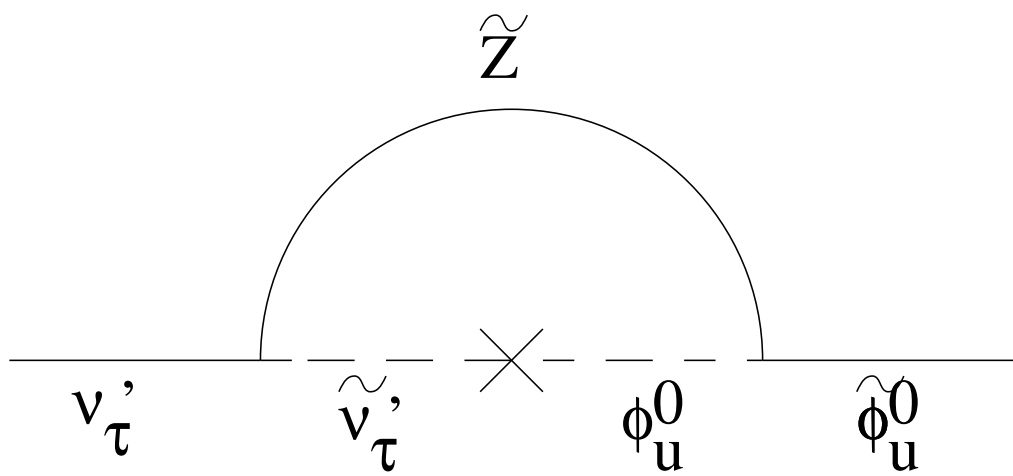


Fig. 2